PREDICTIONS FOR FERMION-PAIR PRODUCTION AT LEP

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The status of predictions for fermion-pair production at LEP is summarized with emphasis on LEP2 energies and on the physics interest there. Some numerical comparisons with other programs are performed. We also present first results of a semi-analytical recalculation of photonic corrections with acollinearity cut in the `ZFITTER` approach.

1 Introduction

Since RADCOR'96, the era of high precision measurements of fermion-pair production at the Z resonance has been finished. For latest results on precision tests of the Standard Model physics, see [1,2,3]. At LEP2 the Z resonance region is left behind with counting rates being a factor of thousand or so smaller. Correspondingly, precision demands for the predictions are weakened; see Table 1. A summary of Standard Model predictions for fermion-pair production at LEP2 may be found in [4]. The hard photonic bremsstrahlung is no longer suppressed, the initial-final state interference corrections reach the order of a percent, and weak virtual corrections are also enlarged and show subtle dependences on kinematics. The interest in fermion-pair production at LEP2 focuses on searches for virtual signals from New Physics. First results have been reported recently.

1.1 The γZ Interference and M_Z

In a model-independent approach, there is a strong correlation between M_Z and the γZ interference term $\mathcal{J}$ in total cross-sections: [5]

$$\sigma_T^0(s) \sim \frac{\alpha_{em}^2(M_Z)}{s} + \frac{\mathcal{R}s + \mathcal{J}(s - M_Z^2)}{|s - M_Z^2 + iM_Z\Gamma_Z(s)|^2}. \quad (1)$$

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Table 1: Some observables for fermion-pair production at LEP. Experimental accuracies are given in square brackets. For LEP1 the total experimental error is shown, for LEP2 the estimated statistical error per experiment based on present efficiencies.

	$\sqrt{s} = M_Z$ unfolded, Z only		$\sqrt{s} = 189$ GeV no cut		$\sqrt{s} = 189$ GeV $\sqrt{s'/s} > 0.85$	
σ_{had} [pb]	41 486	[0.14%]	102.1	[0.8%]	22.1	[1.7%]
σ_μ [pb]	1 996	[0.17%]	9.43	[3.0%]	3.07	[4.6%]
$R_b = \sigma_b/\sigma_{had}$	0.2156	[0.34%]	0.184	[2.0%]	0.1651	[3.6%]
A^μ_{FB}	0.0164	[0.0013]	0.228	[3.1%]	0.585	[4.0%]
N_{had}	14.800 k		16700		3600	
N_{lep}	1.600 k ($e+\mu+\tau$)		1150 (μ)		450 (μ)	

This correlation has been studied at LEP energies. The hadron production data allow to deduce from (1) ([6] and references therein):

$$M_Z = 91\,188 \pm 3 \pm 2.7 \;\text{ MeV}. \tag{2}$$

When determined from the Z peak data alone, the error in (2) is $\pm 3 \pm 13$ MeV. The Standard Model fit yields $M_Z = 91186.7 \pm 2.1$ MeV [7] where the $Zf\bar{f}$ couplings and thus $\mathcal{J}$ in (1) are fixed. The very good agreement of the two fit procedures is a valuable test of the Standard Model.[8]

1.2 Virtual Effects due to New Physics

LEP2 has some potential for the observation of new virtual effects in the $2f$ final state. Recent results are summarized in [6,9] and references therein:

- Heavy neutral Z' bosons may be searched for in two respects.[10,11] At the Z peak, limits on a ZZ' mixing angle may be derived, typically $\theta_M <$ O(few parts per mil). While, at LEP2 limits on the Z' mass are obtained in the range $M_{Z'} > 270 - -820$ GeV depending on the models studied.

- A limit on the energy scale Λ at which contact interactions could appear is $\Lambda > 4 - 10$ TeV. Typical limits from atomic parity violation searches are $\Lambda > 15$ TeV. They are not sensitive to the $\mathcal{P}$ conserving $VV, AA, LL+RR, LR+RL$ type models.

- Leptoquarks, and also sneutrinos and squarks from supersymmetric theories with $\mathcal{R}$-parity breaking may be exchanged in addition to γ and Z. E.g. the leptoquark mass limits, $m_{LQ} > 120 - 430$ GeV, are for some models competetive with direct searches.

2 Realistic Observables

Cross-sections, $\sigma^0(s)$, and asymmetries, $A^0(s)$, are called *improved Born approximations* or *unfolded observables* if they are free of photonic corrections. *Realistic observables*, $\sigma(s)$, contain the photonic corrections. Examples of numerical programs for the calculation of realistic observables are `ALIBABA`,[12] `BHM`,[13] `KORALZ, KK`,[14,15,16] `TOPAZ0 v.4.3`,[17] `ZFITTER v.5.14`.[18] In the `ZFITTER` approach,[19,20,21,22] we calculate:

$$\sigma(s) \sim \int \frac{ds'}{s} \; \sigma^0(s') \; \rho(s'/s). \tag{3}$$

Here, $s' = m^2_{f\bar{f}}$ is the invariant mass of the fermion pair and ρ some radiator. With `ZFITTER`, a *one-dimensional* numerical integration is performed for three different kinematical treatments of photonic corrections: (i) no cut,[23] (ii) cuts on s' and on the scattering angle ϑ of one fermion,[21,20] or (iii) cuts on the fermions' acollinearity angle, on their energies $E^f = E^{\bar{f}}$, and on $\cos\vartheta$; see Section 5. The effective Born cross-section, $\sigma^0(s')$, may also be chosen according to following approaches: (A) Standard Model,[22] (B) Model Independent,[19] (C) Others (see Section 1.2). Since the last comprehensive review [24] many careful comparisons have been undertaken. For LEP1 applications the theoretical accuracy is now considered to be excellent and sufficient for data samples of $O(10^7)$; for fermion-pair production see [25,26] and for (wide-angle) Bhabha scattering at LEP1 see [27]. A recent overview on precision physics at LEP is [28]. For the Monte-Carlo approach see [29,15,16]. We would also like to recommend to regularly consult home pages or `afs` accounts of the Dubna/Zeuthen group (e.g. [30] or [31]), the Krakow/Knoxville group (e.g. [32]), the Torino/Pavia (e.g. [33]) group, and also of the LEPEWWG ([34]).

3 The $Zb\bar{b}$ Vertex at LEP2

An instructive example for different behaviour of the weak corrections on and off the Z peak is $b\bar{b}$ production. The corrections differ from those to $d\bar{d}$ production due to the huge t-quark mass and may be described at LEP1 with formulae derived for the Z width.[35,19,24] At higher energies, there are further contributions of similar size from the $\gamma b\bar{b}$ vertex and from the W^+W^- box. Further, one has to take into account the s-dependence of the vertices and for the box also the angular dependence. The net effect is taken into account in `ZFITTER` since v.5.12 and is shown in Fig. 1. It may be switched off with flag `IBFLA`=0. It amounts to about 2–4 % and is thus of the order of the statistical error; see Table 1.

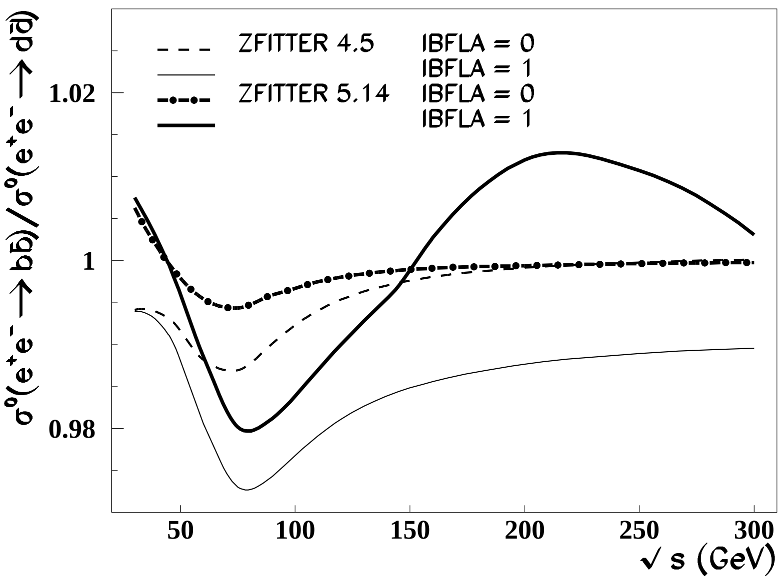

Figure 1: Ratios of improved Born cross-sections for $b\bar{b}$ and $d\bar{d}$ production from ZFITTER v.4.5 (1992) and v.5.14 (1998); the latter has the correct t mass dependence at LEP2.

4 Photonic Corrections with Acollinearity Cut: Comparisons

For the analysis of experimental data the treatment of kinematical cuts on the final particles' phase space is of utmost importance. A variety of numerical comparisons for LEP1 may be found in [19]. Later, the s'-cut was studied for LEP1 in [24]. Numerical results with acollinearity cut are given in Table 3 of [27] for the s-channel part of Bhabha scattering. In Fig. 2, we compare this with ZFITTER v.5.14. and get very good agreement. For LEP2, the s'-cut is estimated to be 'under control' in [4] while a warning was given there that 'the agreement between TOPAZ0 and ZFITTER somehow degrades when implementing an acollinearity cut'. However, one should mention here that both programs were originally designed for applications around the Z resonance and using them at higher energies deserves dedicated checks and, if necessary, further improvements. For a wider energy range, including LEP2, a comparison of σ_T and A_{FB} from ALIBABA v.1 (1990) and ZFITTER v.4.5 (1992) shows deviations up to 10% for the acollinearity cut option at energies above the Z resonance.[36] Within the present study, we add some numerical comparisons

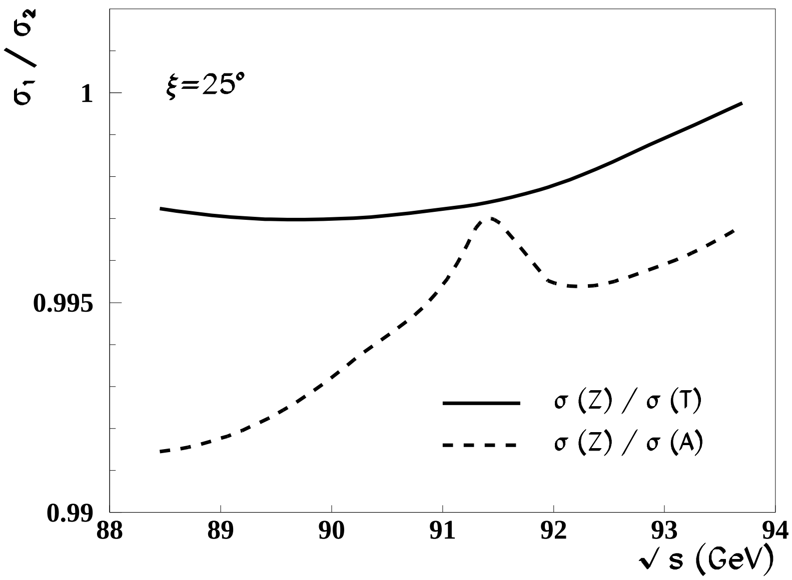

Figure 2: Ratios of s-channel contributions to Bhabha scattering at LEP1: `ZFITTER` v.5.14 versus `TOPAZ0` and `ALIBABA`.

of `ALIBABA`, `TOPAZ0`, and `ZFITTER` over a wide energy range.[37] `ALIBABA` v.2 (1990) was used with the default settings and in `ZFITTER` v.5.14 we modified one flag (`PHOT2`=2). `TOPAZ0` v.4.3 was run in accordance with `ZFITTER` v.5.14. Fig. 3 shows cross-section ratios as functions of s with parameter ξ, the cut on the maximal acollinearity angle between the fermions. The gross features of the 1992 comparison are retained with the new program versions. Between about 100 GeV and 200 GeV, the deviations in the predictions from different programs are huge and heavily depending on ξ, here shown for $\xi = 10^\circ, 25^\circ$. The ratios stabilize at higher (or smaller) energies. In addition, we show at 120 GeV selected predictions arizing from a variation of flags (`IORDER,NONLOG,IFINAL`) in `ALIBABA`: upper ones at (4,n,m), lower ones at (3,n,m), with n=0,1, m=1,2 (best choice: (4,1,2)). This visualizes the strong dependence of predictions on the details of the theoretical input chosen, e.g. the treatment of higher order contributions or the correct inclusion of non-logarithmic $O(\alpha)$ corrections. Evidently, the largest deviations arise from the radiative return of $\sqrt{s'}$ to the Z resonance due to hard initial state radiation. Interest in the high energy part of the data anyhow means to cut this away and so there shouldn't be a

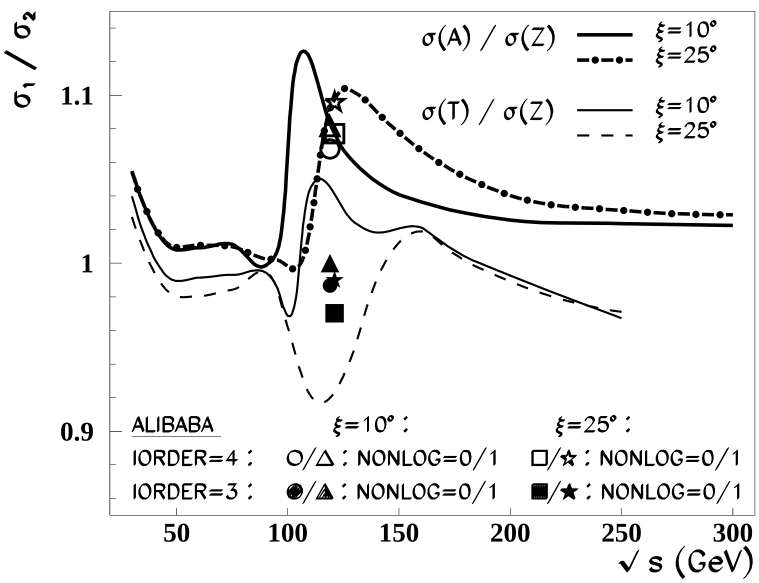

Figure 3: Numerical comparison of `ALIBABA` v.2, `TOPAZO` v.4.3, and `ZFITTER` v.5.14 as functions of s with two settings of acollinearity cut ξ ($40^\circ < \theta^{\bar{f}} < 140^\circ$). At $\sqrt{s} = 120$ GeV, we also show data points for variations of flag settings (i,n,m) in `ALIBABA` as discussed in the text.

serious problem. If instead one is interested in the radiative return, one has to be concerned about accuracies. These observations confirm similar statements from other studies.[38,39]

5 Semi-analytical Approach to the Acollinearity Cut

A sketch of the analytical formulae with acollinearity cut coded in `ZFITTER` is given in [40]. Since some simplifications were made which were intended for applications near the Z, we now recalculate the corresponding $O(\alpha)$ corrections. The kinematics were derived in [41]. One has to perform a three-fold analytical integration of the squared matrix element over one photonic angle, over the invariant mass x of (fermion+photon) in the cms, and over the fermion's scattering angle. The Dalitz plot is shown in Fig. 4 ($v_2 = x$).

The cross-section is the sum over three regions in phase space:

$$\sigma(s) = \left[\int_{\mathrm{I}} + \int_{\mathrm{II}} - \int_{\mathrm{III}} \right] \; ds' \; dx \; d\cos\vartheta \frac{d\sigma(A)}{ds' dx d\cos\vartheta}. \tag{4}$$

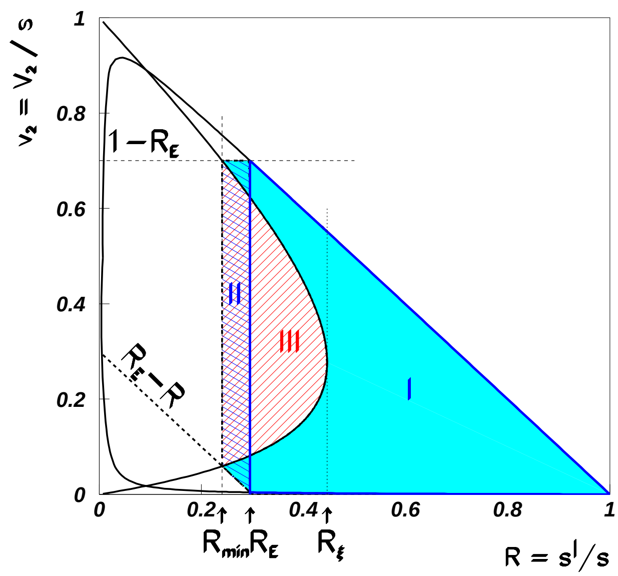

Figure 4: Phase space with acollinearity cut and (lower) muon energy cuts.

Parameter $A = A(s'/s)$ has different meaning in these regions:

$$A_{\rm I} = 1, \tag{5}$$

$$A_{\rm II} = (1 + R - 2R_E)/(1 - R), \tag{6}$$

$$A_{\rm III} = [1 - R(1 - R_\xi)^2/(R_\xi(1 - R)^2)]^{1/2}, \tag{7}$$

with $R_E = 2E_{min}/\sqrt{s}$, $R_\xi = (1 - \sin(\xi/2))/(1 + \sin(\xi/2))$, and $R = s'/s$. We have (preliminary) results for the numerically largest initial state corrections and see deviations from the old results in the hard bremsstrahlung σ^{hard}. For the total cross-section, e.g., the analytical formula with cuts on acollinearity and minimal fermion energy is remarkably compact for the full angular acceptance ($c = 1$). In each of the three regions, it is:

$$\sigma_T^{hard}(s, \xi, E_{min}) = \frac{3\alpha}{4\pi} Q_e^2 \int dR \; \sigma_T^0(s') \; \rho_T(R, A), \tag{8}$$

$$\rho_T(R, A) = \left(A + \frac{A^3}{3} \right) \frac{1 + R^2}{1 - R} \left(\ln \frac{s}{m_e^2} - 1 \right) + (A - A^3) \frac{\mathcal{B}R}{1 - R}, \tag{9}$$

with $\mathcal{B} = 2$. For $A \to 1$, the phase space regions II and III do not contribute and (9) approaches the well-known result derived in [42]. The additional contributions from final state radiation and the initial-final state interference to σ_T (and also those to σ_{FB}) may be found in [23] for $A = 1$. The other generalizations for $A \neq 1$ will be published elsewhere. Some analytical formulae for the final state corrections are given in [43]. We have to mention that, differing from (9), the coding in `ZFITTER` corresponds to $\mathcal{B} = 4/3$ if one looks there into the limit $c = 1$. The resulting numerical deviations are typically of the order of 0.5% to 2%. They do not lead to drastical improvements of the comparisons shown in Section 4.

6 Summary

We gave a brief overview on recent developments of predictions for fermion-pair production at LEP and on some physics results from LEP2. Predictions at LEP2 energies when applying an acollinearity cut are discussed in more detail. First results of a recalculation of the analytical formulae for hard photon corrections in `ZFITTER` with acollinearity cut are presented. The numerical effects are of the order of 1%. The need of further investigations is stressed.

An extended version of this contribution is [37].

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